Design of structural slabs with significant differences in bearing heights

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Abstract. This article is devoted to the design methods of spatial metal structures and non-standard supports for them in conditions of significant difference in the location of elevation marks of bearing points. Several analytical models of structural slabs with multilevel support were built, and the calculation results revealed peculiarities of the operation of these structures and presented constructive solutions for their design. Also, on their basis, unified methods and typical solutions for constructing spatial structures were proposed.

1 Introduction

The application of spatial structures in construction is an actively developing trend due to architectural tendencies to design buildings of curvilinear shapes and large sizes, the cover structures of which require non-standard technical solutions and a non-trivial approach to their realization. In most cases, such buildings are represented by unique social facilities, such as sports facilities, exhibition complexes, and shopping centers, which, due to their functional purpose, require large free spaces in combination with individual design, characterized by curvilinear shapes, acute angles, and other atypical solutions. In the design of such structures, the most significant and labor-intensive is the design of the pavement, which, in most cases, is taken in the form of a structural slab. This type of pavement is characterized by considerable pliability in various geometric shapes while possessing considerable rigidity because it consists of relatively short, rigid rectilinear elements connected at various angles. Due to such a high degree of adaptability to architectural solutions, this type of coating is used to implement various design solutions, including such complex and time-consuming as large-span structures with height differences in the bottom of the structures of several floors. The difficulty of structural slab construction lies in the need for non-standard construction methods, which require a case-by-case approach. However, difficulties in design arise not only with the pavement arrangement but also with their supports, which are often subject to significant lateral displacement in their upper part due to their sparse location and structural conditions [1, 2].

The primary purpose of this paper is to determine the structural performance of structural slabs at significant differences in bearing heights and to derive design methods based on them.

The following plan has been constructed to achieve the objective:

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1) Identification of the most common architectural forms in the construction of large-span pavements with multilevel support;

2) Development of analytical examples of buildings with similar forms;

3) Calculating these models, analyzing the performance of the structures, and determining typical critical moments;

4) Development and formulation of recommended optimal structural methods for such structures based on the analysis performed

2 Materials and methods

The sphere of construction production does not stand still and is rapidly developing in all its aspects, which manifests itself in the development of new building materials, technologies, equipment, and much more, allowing to create unusual architectural forms and get away from simple rectangular solutions. Such forms have become widespread in constructing unique large-span buildings designed to create the most unusual architectural solutions [3].

Today, many unique large-span buildings have been built, each of which has its own individual design, and a special place among them are structures characterized by significant height differences and angles of inclination of the pavement. Examples of such buildings are the Iceberg Ice Palace (Sochi, Russia), the Heydar Aliyev Center (Baku, Azerbaijan), and the Harbin Opera House (Harbin, China) (Figure 1). However, despite the significant difference in their external appearance, if we consider their internal structure, we can notice similar design solutions in the structural part, i.e., the structures' operation principle remains unchanged [4].

Fig. 1. a – Iceberg Ice Palace; b – Heydar Aliyev Center; c – Harbin Opera House.

The structural part of such structures looks as follows – the main load-bearing part is represented by a reinforced concrete core of rigidity, which serves as a base support for the cover at its highest point, and the metal is mainly used for the cover and posts, which provide support for curvilinear forms. The top edge of the core has a variable height that gradually decreases, providing a steeply sloping structural slab. In addition, the core supports the metal columns on which the pavement is mounted, and nearby columns are fastened to it by means of horizontal elements to reduce their flexibility. Further, with the lowering of the pavement support level, the supporting columns are tied together by introducing ties to create a single rigid system. The structural slab usually ends at the ground surface, where the support is either a dense system of closely spaced columns or the slab itself in the form of a powerful support node consisting of a cross-sectional system of elements with cross-sectional areas many times larger than the cross-sections of the main elements of the pavement, which is due to the greatest forces and stress concentrations in this place. Another design feature is the arrangement of a curved convex part at the highest point of the pavement to create a spread, reduce deflections in the central part, and distribute the main forces in the support part [5].

3 Results

3.1 Analytical modeling

Having analyzed the primary examples from the world experience in the design of multilevel large-span buildings, it is possible to distinguish 2 most used structural schemes:
1 – buildings with a smooth curvilinear transition of the structural slab from horizontal to vertical position, where the slab acts as both a covering and main load-bearing support;
2 – buildings with a sloping structural slab, which rests on a system of vertical load-bearing elements of variable height.

Based on these design features, an analytical building model was developed to analyze the performance of the structural slabs to account for these features.

The model is a two-section building with plan dimensions of 80x55 m (Fig. 2). The sections interface at right angles and have height differences of up to 36 m with a maximum top-of-pavement slab elevation of 87,000. In this case, their coating is made in the form of a common coating plate, a broken surface consisting of triangles connected along the edges.

The structural plate is two parallel metal meshes at a distance of 0.8 m between each other with diamond-shaped cells, displaced relative to each other in terms of half a cell and connected by rod elements, with the length of ribs in a cell from 0.42 m to 2.73 m. In this case, the shape of the cells is oriented so that the two edges of the rhombus are parallel to the plate fracture point [6].

The slab is supported by "bushes" of steel columns directed in different directions at an angle to the nearest pavement nodes, converging in the lower part at a common point, resting on the reinforced concrete frame of the building. The supports are mainly located at the corner points of the building, where the greatest rigidity of the frame is achieved, and also to create a large unsupported space. The vertical part has support points in its lower and upper parts at the places of its transition to the horizontal position [7].

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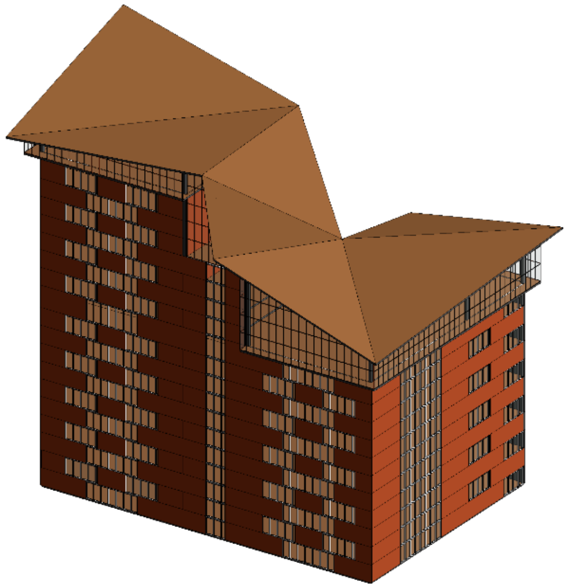

Fig. 2. 3D building model for the analytical example.

Based on these geometric parameters, an analytical model of the structural slab was developed to calculate further and consider the structural performance (Fig.re 2). A system of rod finite elements represents the model hinged at the ends. Two types of stiffeners are used in the model: seamless hot-deformed steel pipes (GOST 8732-78 with changes No. 1, 2) for the upper and lower mesh, as well as for the connecting rods with the cross-section Ø152x10 mm, for the branches of support posts Ø219x10 mm.

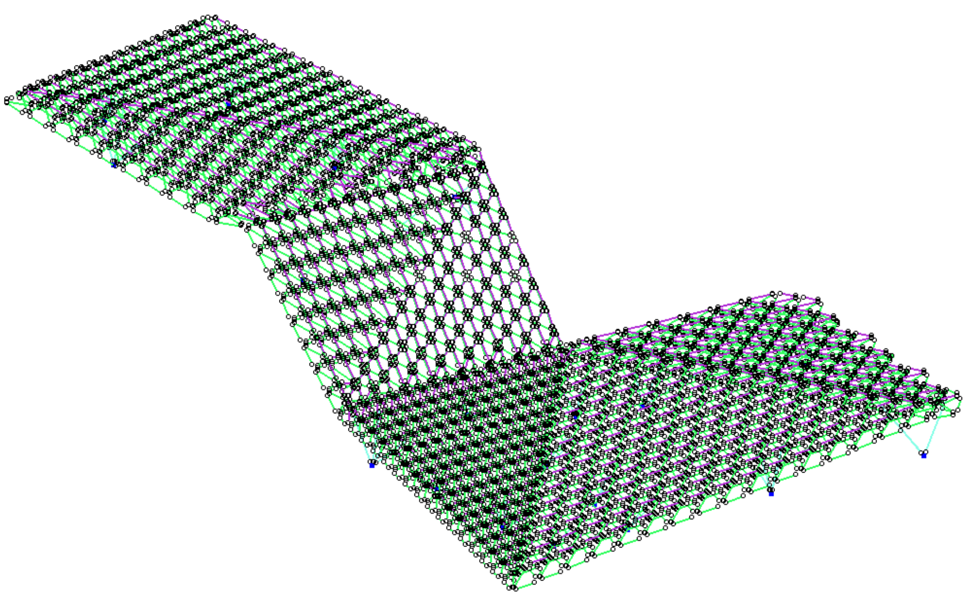

Fig. 3. Analytical model of a structural slab.

3.2 Analyzing the structure performance

After building the analytical model in the LIRA SAPR software package, this model was calculated, and the performance of the structure was analyzed for the following parameters: maximum and minimum stresses in the structure, longitudinal forces in the rods, the highest loads on the supports, and displacements of the structure along the vertical axis.

Inspection of the stress distribution in the structure (Fig. 4) showed that in the upper mesh, the number of compressed bars is approximately equal to the number of tensile bars, with the tensile bars located near the supports and the compressed bars concentrated in the span at the junction of the triangular plates. The maximum value of the longitudinal tensile force was in the bars closest to the support columns near the console with the largest outreach and amounted to 97.3287 kN; the maximum compressive force occurred in the bars near the lower transition of the vertical part of the slab to the horizontal and amounted to 76.46 kN.

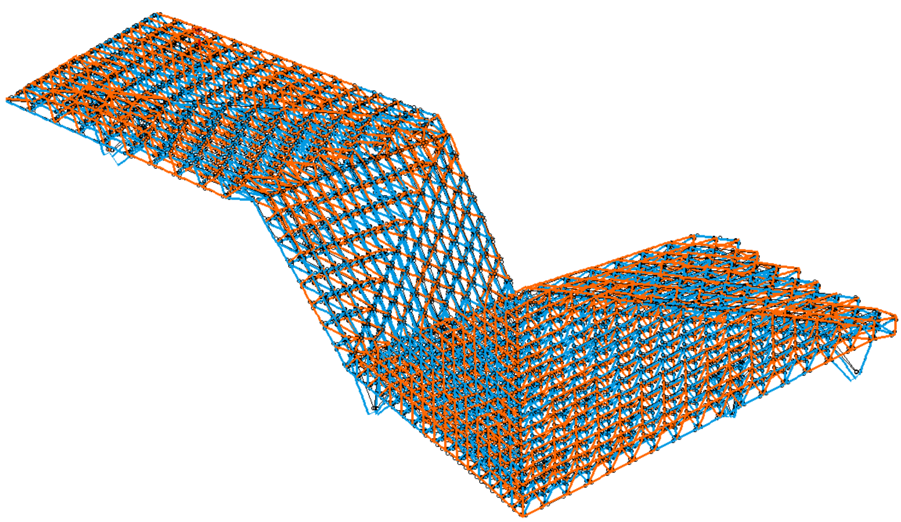

Fig. 4. Distribution of longitudinal forces N in rods.

Analysis of the performance of the bottom grid showed that the rods in it are predominantly in compression, and the highest force, equal to 84.42 kN, also occurs in the vertical part of the slab closer to the fracture points. The difference between the longitudinal compressive forces in the upper and lower meshes was 9.43 %.

The maximum forces of the entire system are concentrated in the support columns, which concentrate the forces from the structure’s weight. The highest value in this case is 223.01 kN, which is 2.64 times larger than the mesh forces.

The analysis of the deformation pattern of the structures (Fig. 5) showed that the largest displacements along the vertical axis Z are characteristic of the cantilevered parts of the structure, as well as in the spans between the supports and the locations of fractures. The displacements in the vertical slab element have values close to the average values of the total deflections, which is explained by the reinforced support both on the columns and on the underlying pavement elements, as well as by the diagonal bend in the middle of this part, which increases the stiffness of the structure.

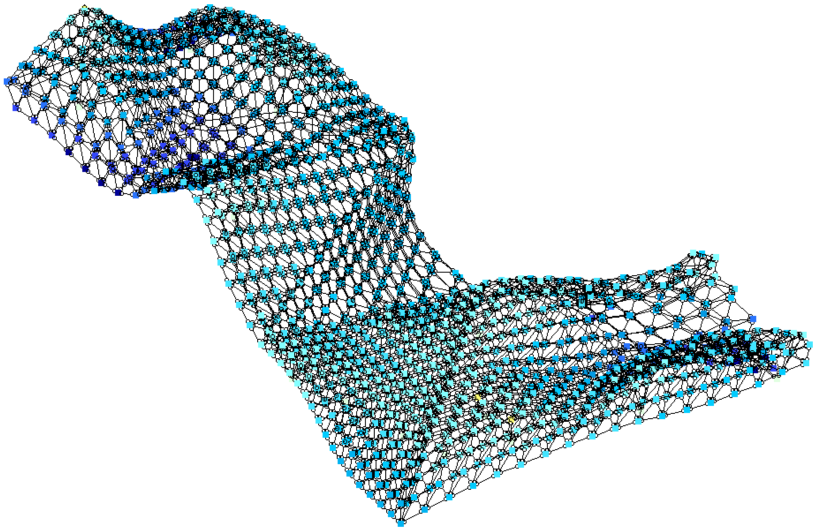

Fig. 5. Deformation scheme.

4 Conclusion

Having analyzed the design solutions of the structures of the existing unique large-span buildings and structures characterized by significant height differences of supporting points, as well as analyzing the analytical model built based on the studied structural schemes, we can identify several features in the work of these structures, based on which to make recommendations for the design of such structures.

The main recommendations, in this case, should, first of all, include the shape of the pavement, which largely determines the selection of the necessary dimensions of the structural slab, the distribution of forces on the structure, the shape and size of the cross-sections of the elements, and much more. The main requirement for the shape of the cover is the presence of convex breaks or roundings in its middle part, increasing the rigidity of the structure by generating spacing forces.

The following design recommendation concerns the support sections of the structural slabs, which concentrate the main forces. First, the support elements should be located at the structure's corners to create a larger span. However, they should preferably have significantly developed cantilevers to counterbalance the main span structures. Secondly, the structural slab elements near the supports should have a higher value of cross-sectional area relative to the bars in the span section. In cases with high stresses at the support, provision should be made to replace some elements with others with a stiffer cross-section.

A final important recommendation is the construction of a rigid reinforced concrete core, which should serve not only as a resting point for the highest point of the pavement but also as an element for anchoring the structural slab at intermediate levels.

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